Brookhaven National Laboratory

U.S. DEPARTMENT of ENERGY

Extraction Bump Digital Twin for NSRL slow extraction

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6th Slow Extraction Workshop

Oct 6-9, 2025

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Introduction to NSRL

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NASA Space Radiation Laboratory (NSRL)

- Understanding the risks and uncertainties from the space radiation environment is crucial for NASA missions:
- *"In space, astronauts are exposed to ionizing radiation that is quantitatively and qualitatively different from terrestrial radiation. This environment includes protons and high-Z, high-energy (HZE) ions together with secondary radiation, including neutrons and recoil nuclei that are produced by nuclear reactions in spacecraft materials or tissue."*

- Risk of Radiation Carcinogenesis (2016)
NASA HRP Space Radiation Element

NSRL Users and Experiments:

Three main types of experiments

1. Radiobiology – Primary objective of NSRL and NASA interest in a synchrotron facility
   Users often from university biomedical research labs receiving grants from NASA HRP

2. Microelectronics – Little interest in early years, now represents *majority of beam hours*
   Users from space and defence industry

3. Scientific Measurements – a handful of experiments per year, usually detector testing
   Users often from university or national physics labs

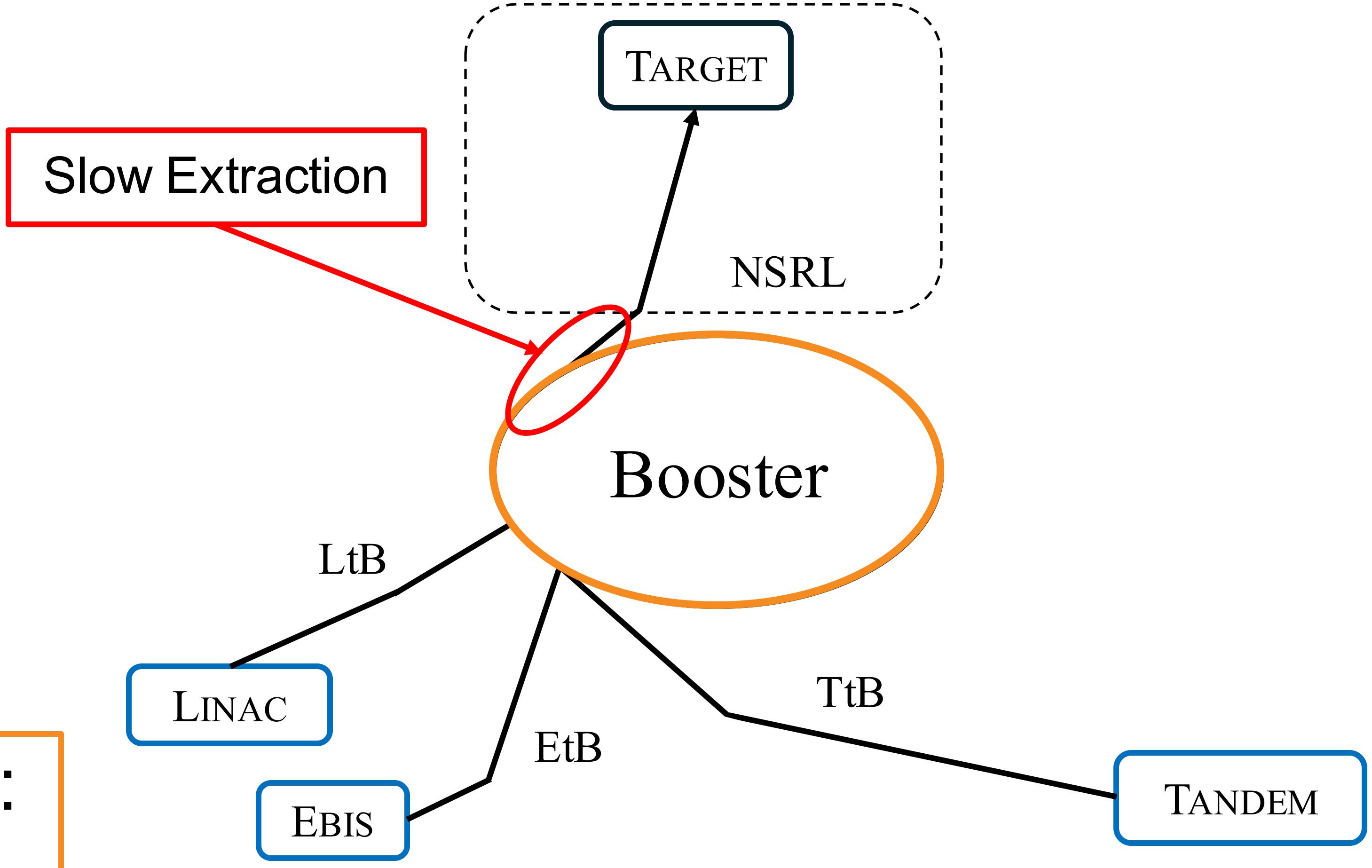
Sources & Synchrotron Complex

Source machines:

Linac (proton)

EBIS (ion)

Tandem Van de Graaffs (ion)

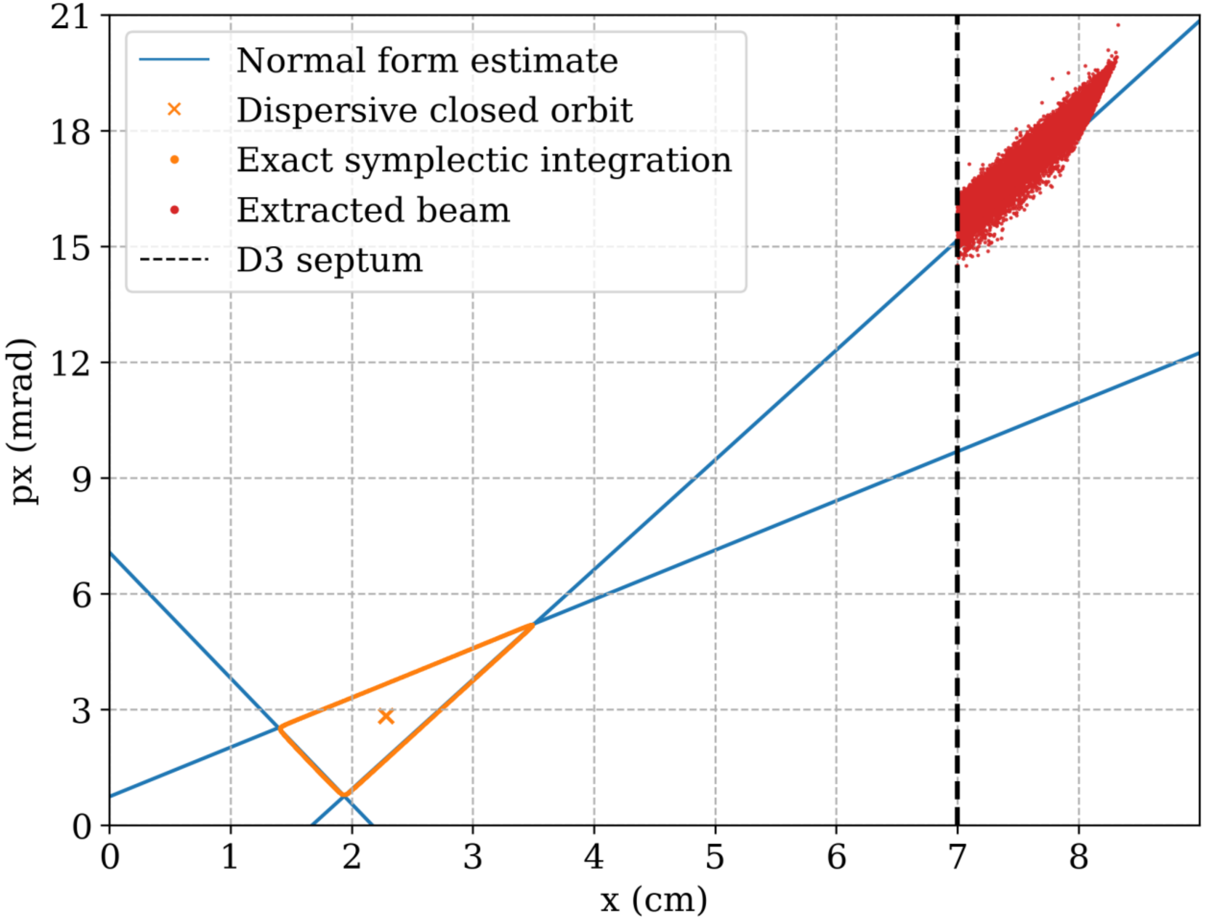


AGS Booster synchrotron:

Accelerate beam to KE between 50 and 2500 MeV/n

Resonant Slow Extraction

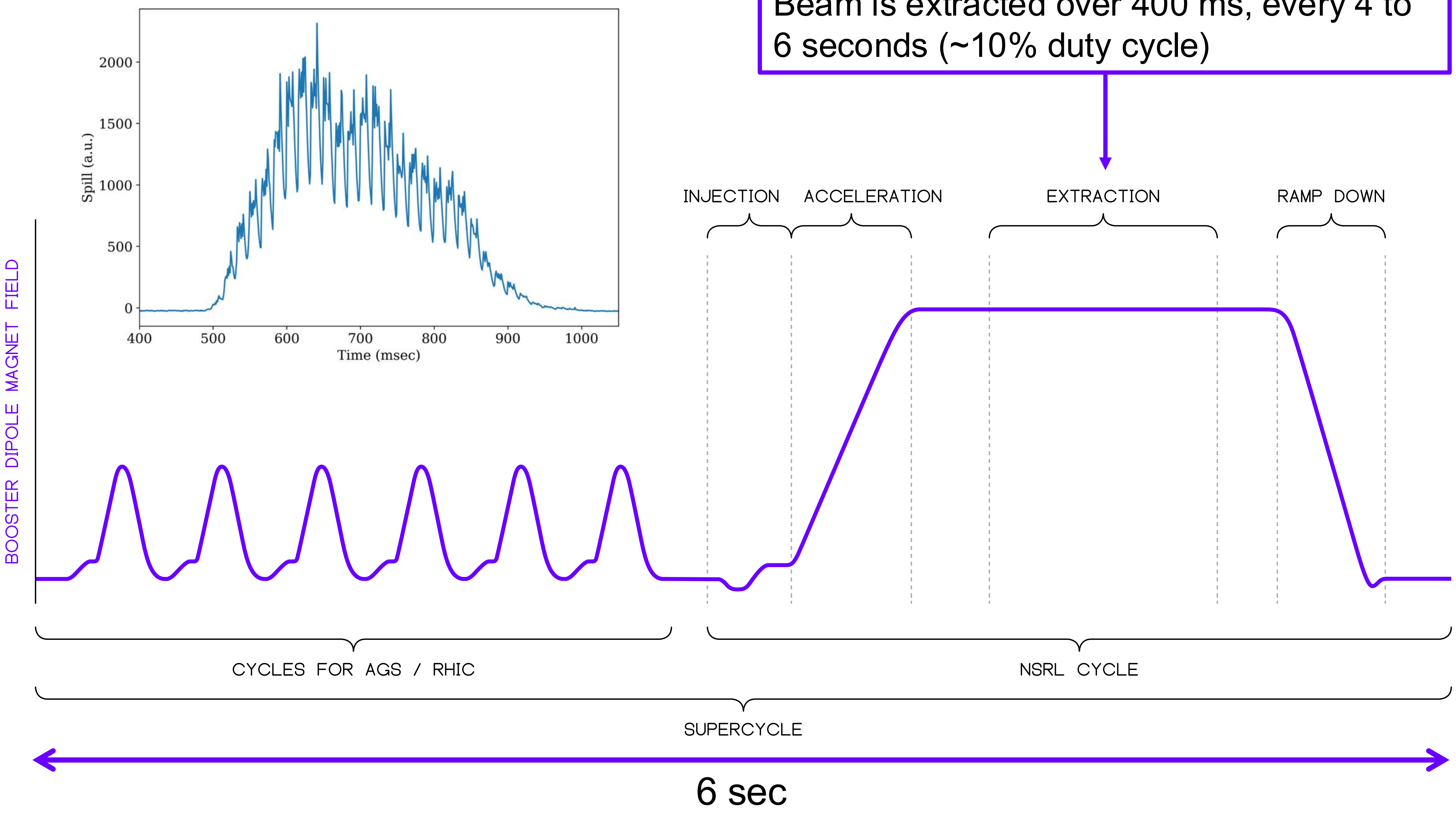
- Thin septum (0.76 mm) at D3 + thick septum (15.2 mm) at D6 in the Booster
- Third-integer (13/3) resonance created by four sextupoles: C8, F8, B4, E4
- Triangular stable region in horizontal phase space, brought closer to the septa via local extraction bump
- Particles with turn-by-turn orbit deviation larger than D3 septum thickness are extracted and kicked into D6 aperture



See Eiad's presentation on SciBmad simulation

Extracted Beam Spill

Beam is extracted over 400 ms, every 4 to 6 seconds (~10% duty cycle)



Booster Extraction Bump

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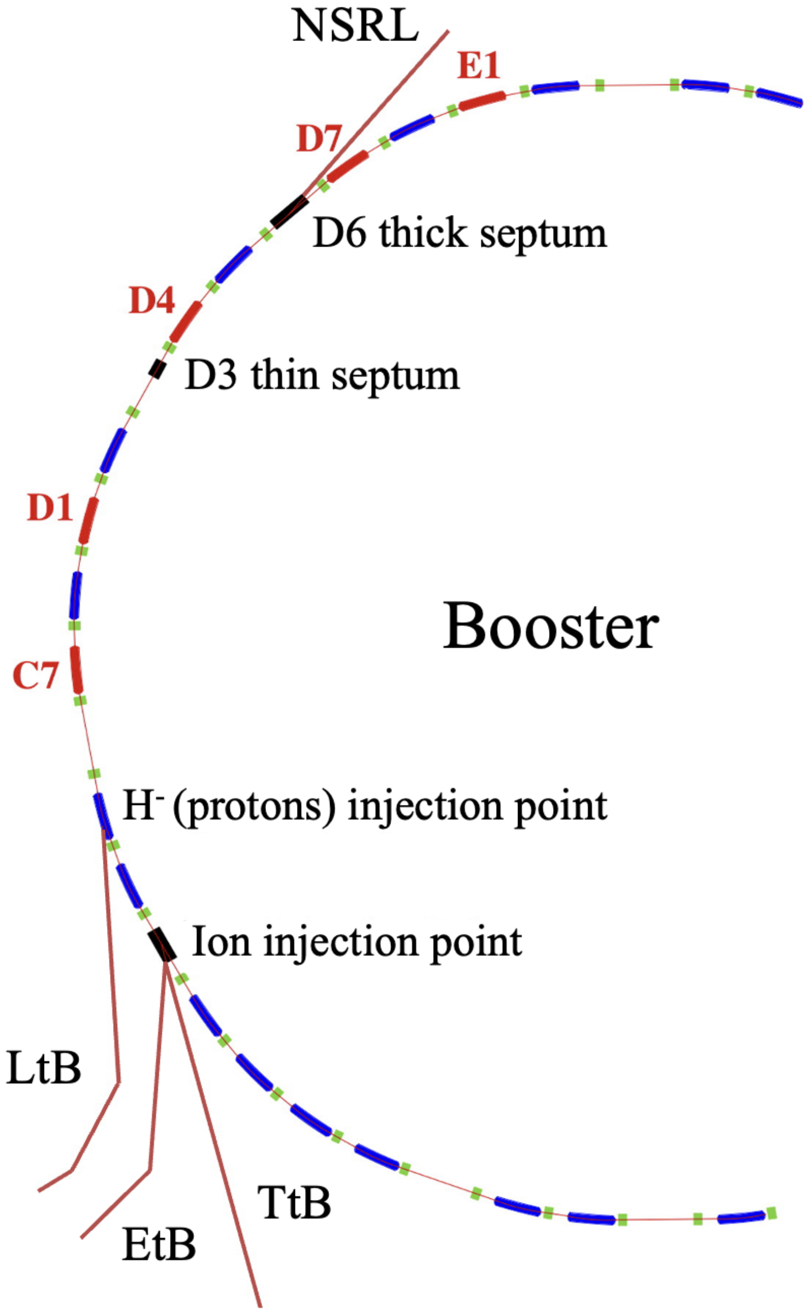
Booster extraction bump

- Local bump via back-leg windings on five Booster main magnets: C7, D1, D4, D7, E1
- Each main magnet has 16 main windings and 2 back-leg windings: $I_{total} = I_{dipole} + \frac{2}{16} I_{bump}$
- Bring closed orbit close to septa at D3 and D6
- Can be simulated in two ways:
  - dipole field errors
  - zero-length horizontal kicker in the middle of dipoles



Orbit distortion via local bump

- When a bump is excited, the main magnet field B is changed, and the closed orbit solution experiences a kick angle θ: $\theta = \frac{\Delta B \Delta s}{B\rho}$

- The new orbit at location s in the Booster with bump on at location k is:

$$x(s) = \frac{\theta_k \sqrt{\beta(s)\beta_k}}{2\sin(\pi\nu)} \cos(|\phi(s) - \phi_k| - \pi\nu) + D(s)\frac{dp}{p}$$

- The new angle at location s is the derivative:

$$x'(s) = \frac{\theta_k \beta_k}{2\sin(\pi\nu)\sqrt{\beta(s)\beta_k}} [\alpha(s)\cos(|\phi(s) - \phi_k| - \pi\nu) + \sin(|\phi(s) - \phi_k| - \pi\nu)] + D'(s)\frac{dp}{p}$$

$$\alpha(s) = -\frac{1}{2}\beta'(s), \phi(s) = \int_0^s \frac{1}{\sqrt{\beta(s)}} ds$$

Design bump strength calculation

- Strengths of the five bumps can be calculated for a design bump with
  - desired location and angle at D3 and D6 septa: $x_{D3},\ x_{D6},\ x'_{D6}$
  - minimal residual orbit in the rest of the Booster ring: $x_{E1} = x'_{E1} = 0$

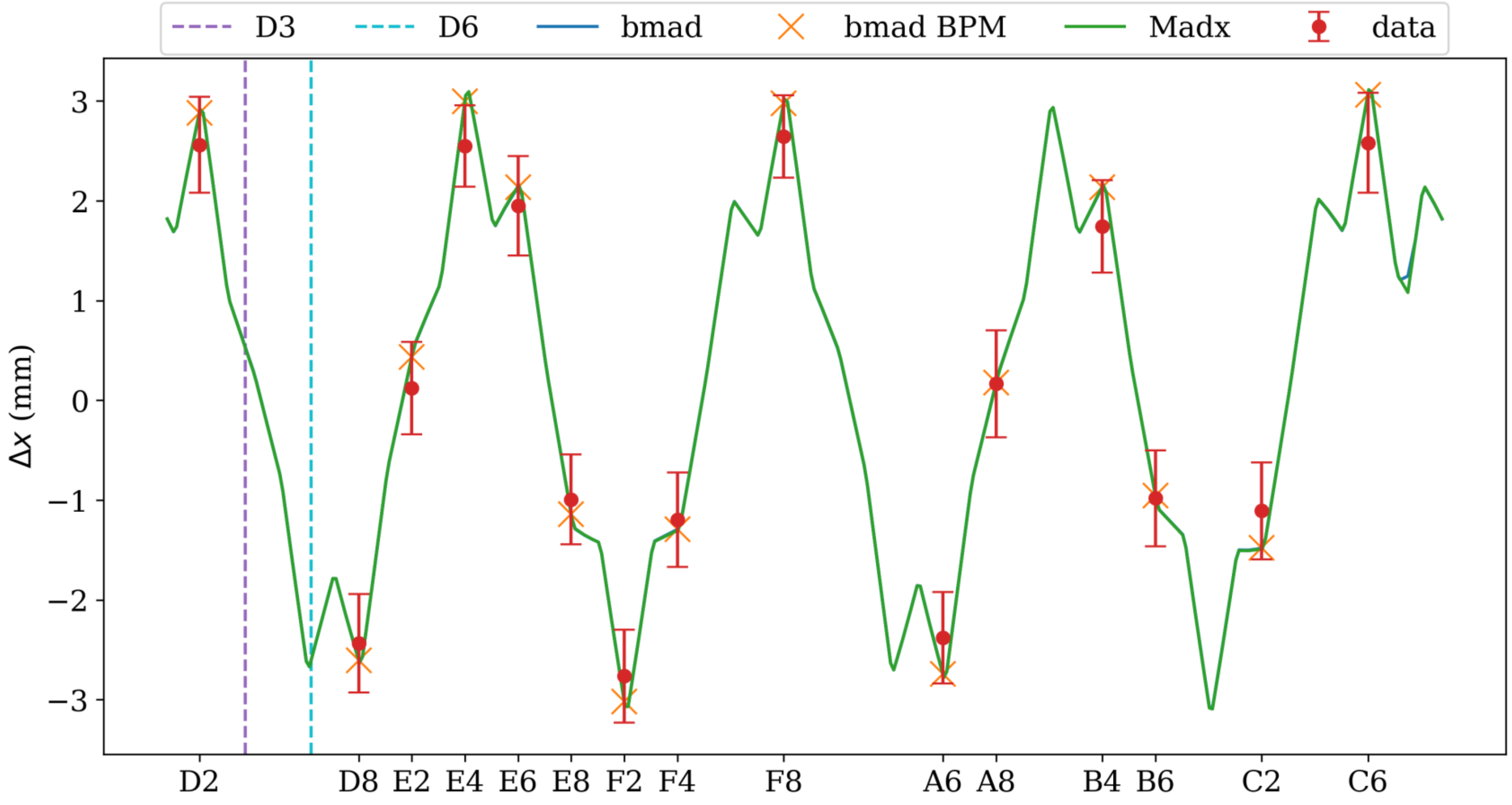
$$\begin{pmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \\ \theta_4 \\ \theta_5 \end{pmatrix} = \underline{A}^{-1} \left[\begin{pmatrix} 0 \\ 0 \\ x_{D3} \\ x'_{D6} \\ x_{D6} \end{pmatrix} - \begin{pmatrix} D_{E1} \\ D'_{E1} \\ D_{D3} \\ D_{D6} \\ D_{D6} \end{pmatrix} \frac{dp}{p} \right]$$

Coefficients of θ_k for location x and angle x' on previous slide

Bump simulation vs. measurement

618 MeV/n Silicon

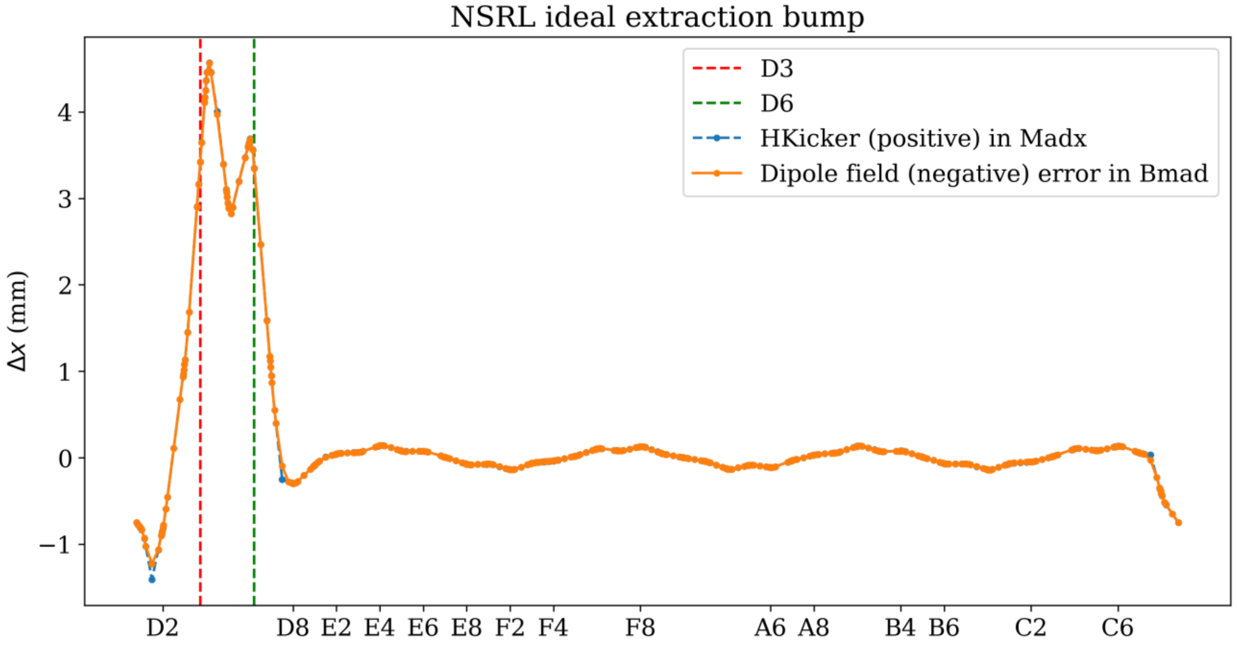
- Single bump measurement (C7 bump = 80 Amp shown) show good agreement with simulation
- Bump defined as horizontal kicker in MAD-X, dipole field error in Bmad

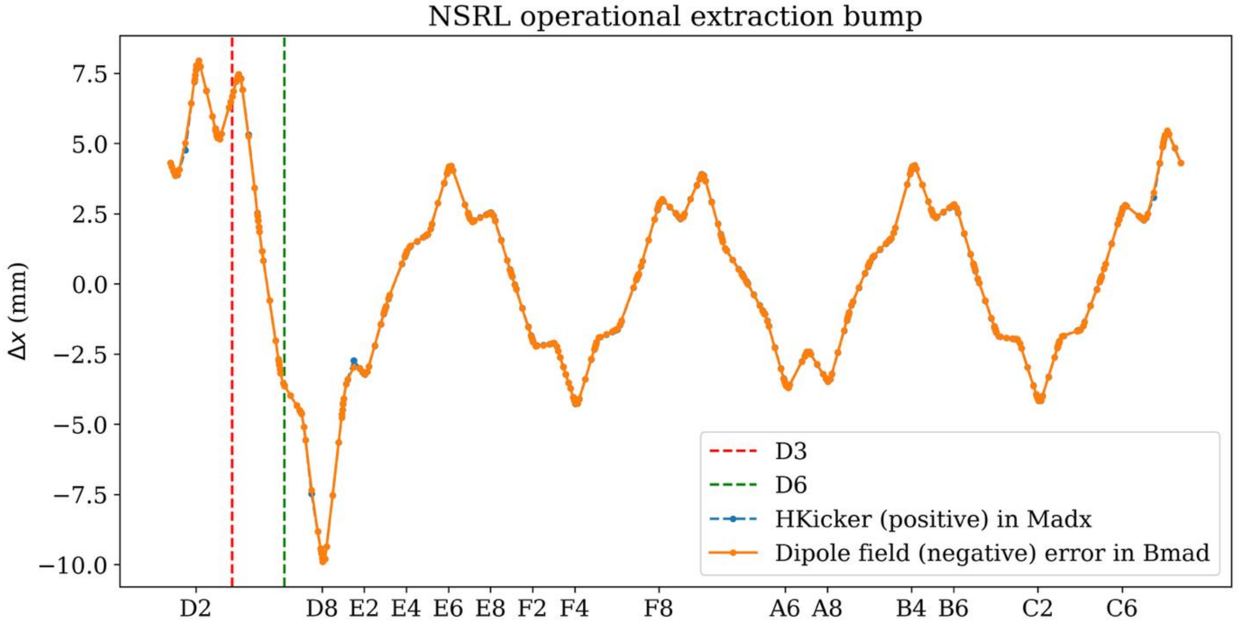


Bump design vs. Reality

618 MeV/n Silicon

- Surprise discovery: operational bump is miles away from design bump due to years of blind tuning



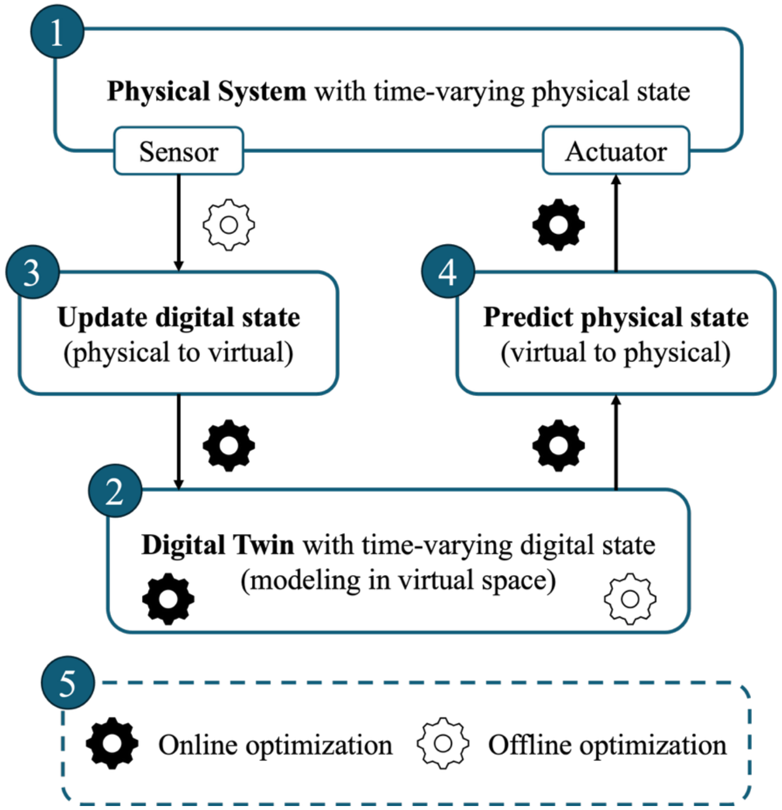


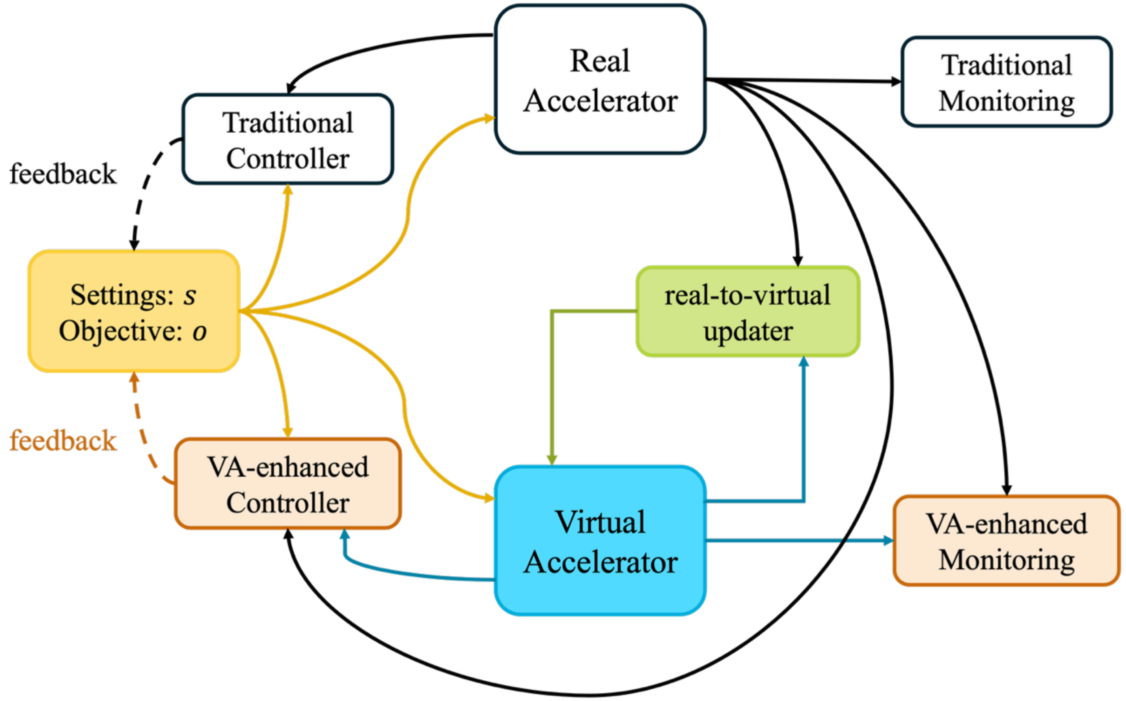
Digital Twin interface

What is digital twin (DT)?

"A digital twin is a set of virtual information constructs that mimics the structure, context, and behavior of a natural, engineered, or social system (or system-of-systems), is dynamically updated with data from its physical twin, has a predictive capability, and informs decisions that realize value. The bidirectional interaction between the virtual and the physical is central to the digital twin."

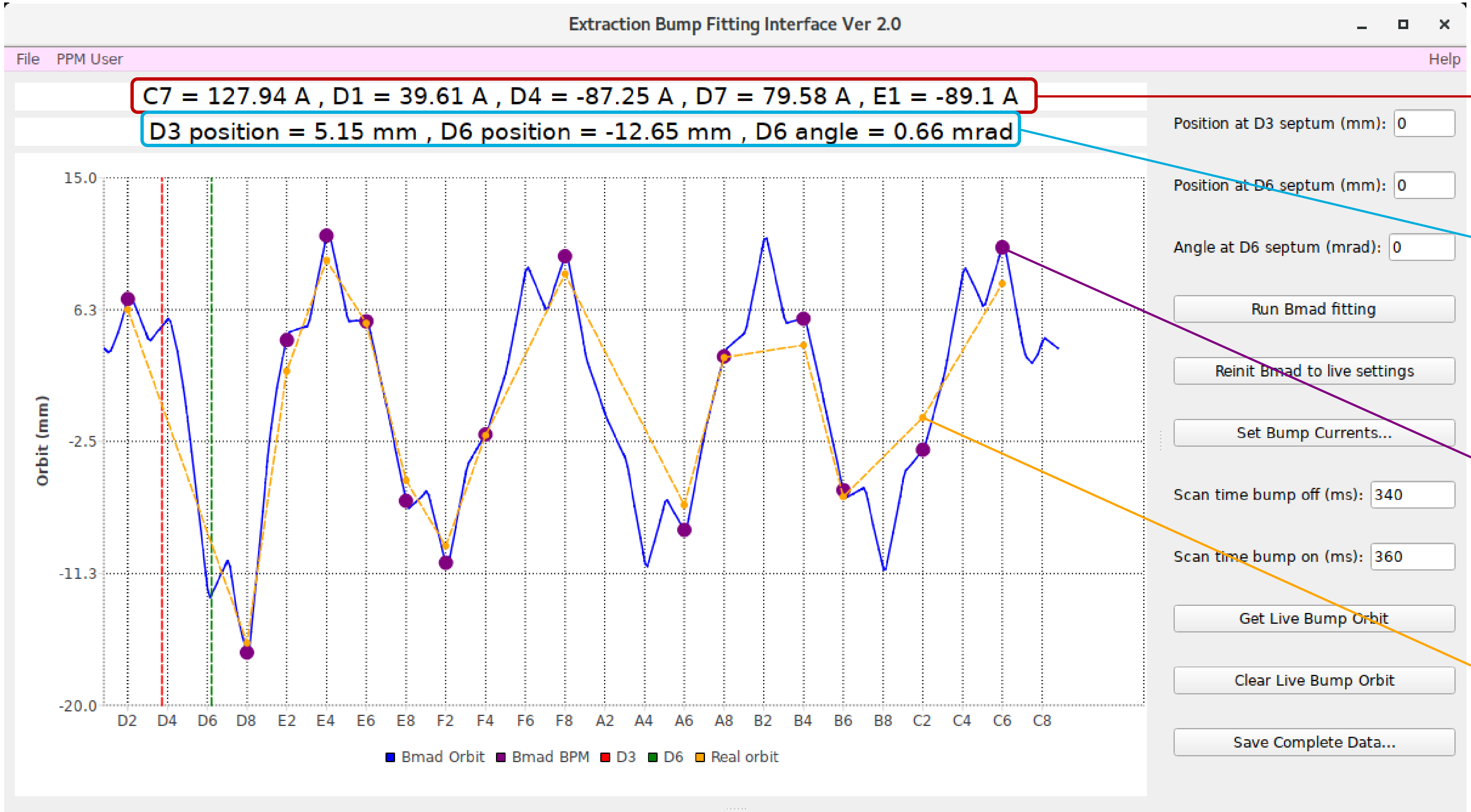
- Foundational Research Gaps and Future Directions for Digital Twins (2024) National Academies of Sciences, Engineering, and Medicine report





Digital Twin for extraction bump

1 GeV/n Proton



Load live bump currents from real machine

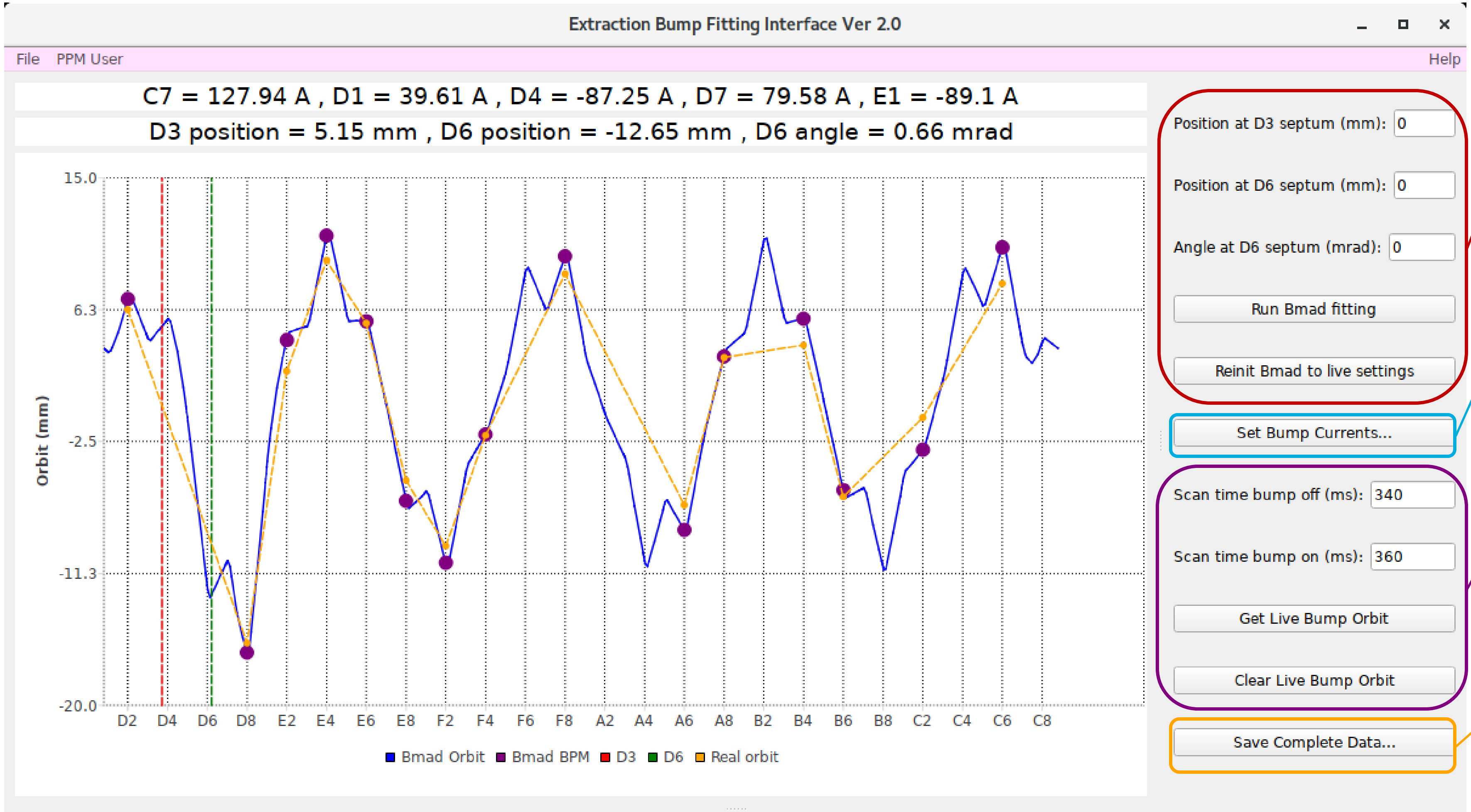
Simulated D3 + D6 orbit info using live bumps

Simulated bump orbit using live bumps

Real bump orbit measured by beam position monitors

Digital Twin for extraction bump

1 GeV/n Proton



Use Bmad to fit any design bump shape

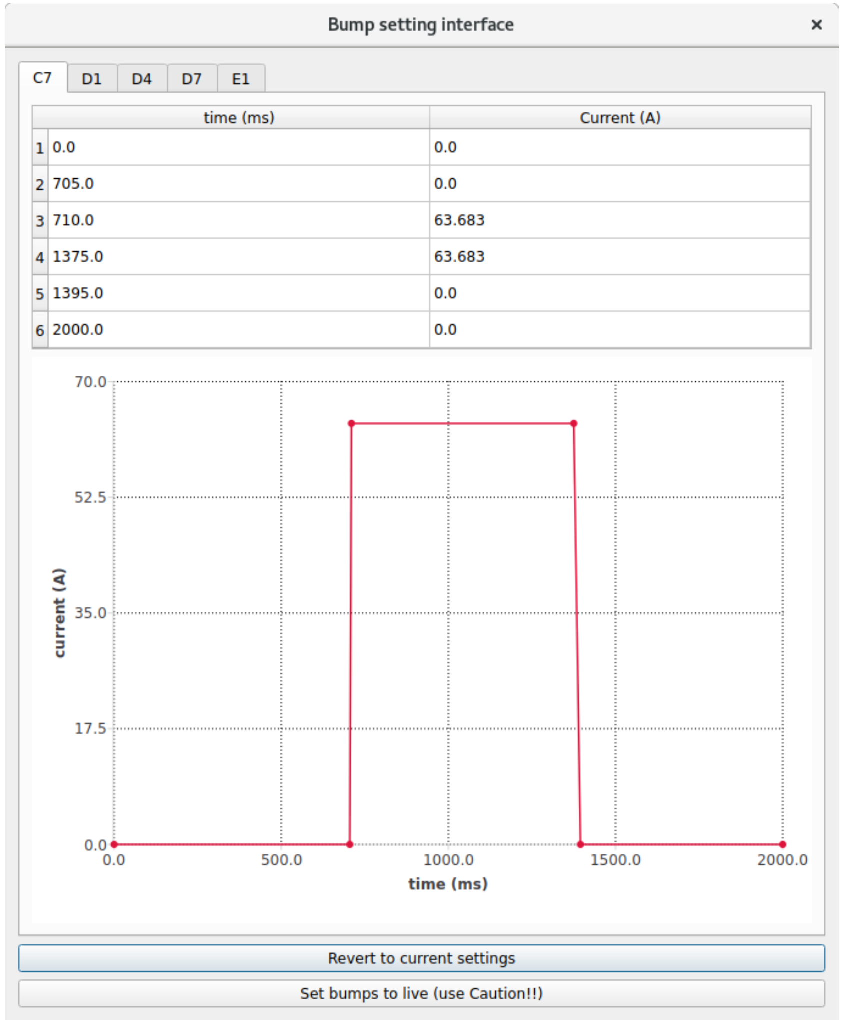
Send calculated bump currents to real machine

Time stamps in Booster cycle used to measure bump orbit

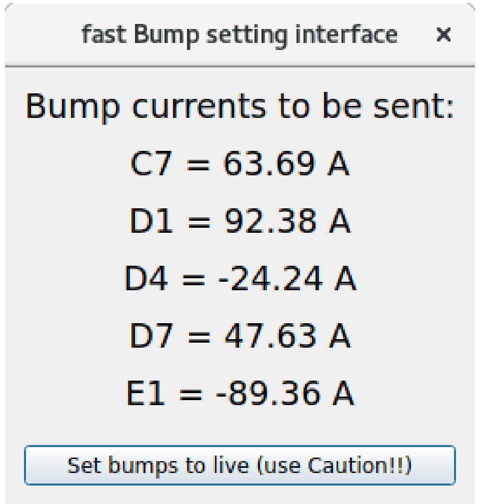
Save simulated and measured data

Digital Twin for extraction bump

370 MeV/n Silicon



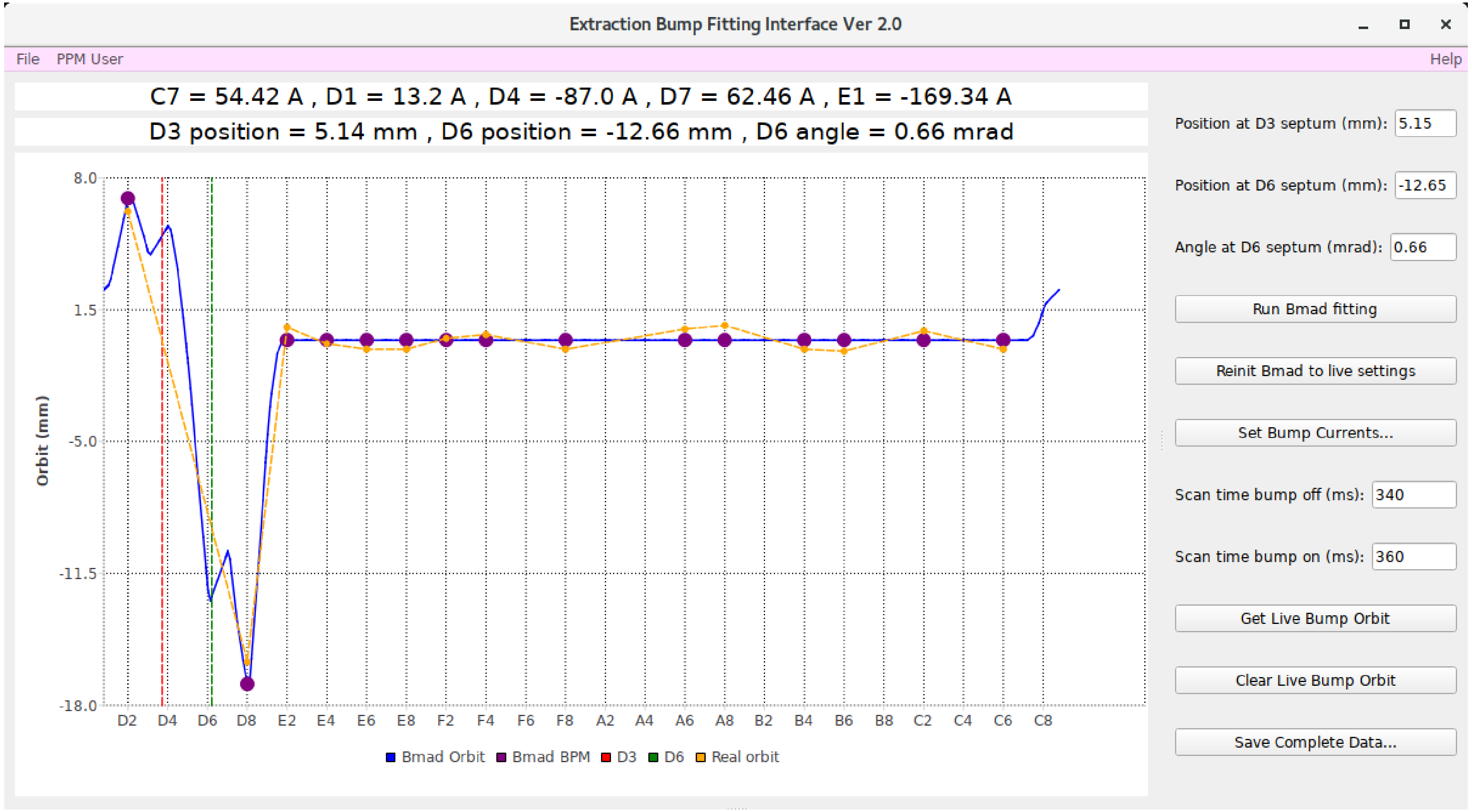
- Booster magnet currents are time-dependent
  - Bump currents are only turned on during NSRL extraction
- Full bump setting interface allows changes to both timing and current
- For normal operation, timing stays the same, fast setting interface allows changes to only current



DT-assisted bump tuning

1 GeV/n Proton

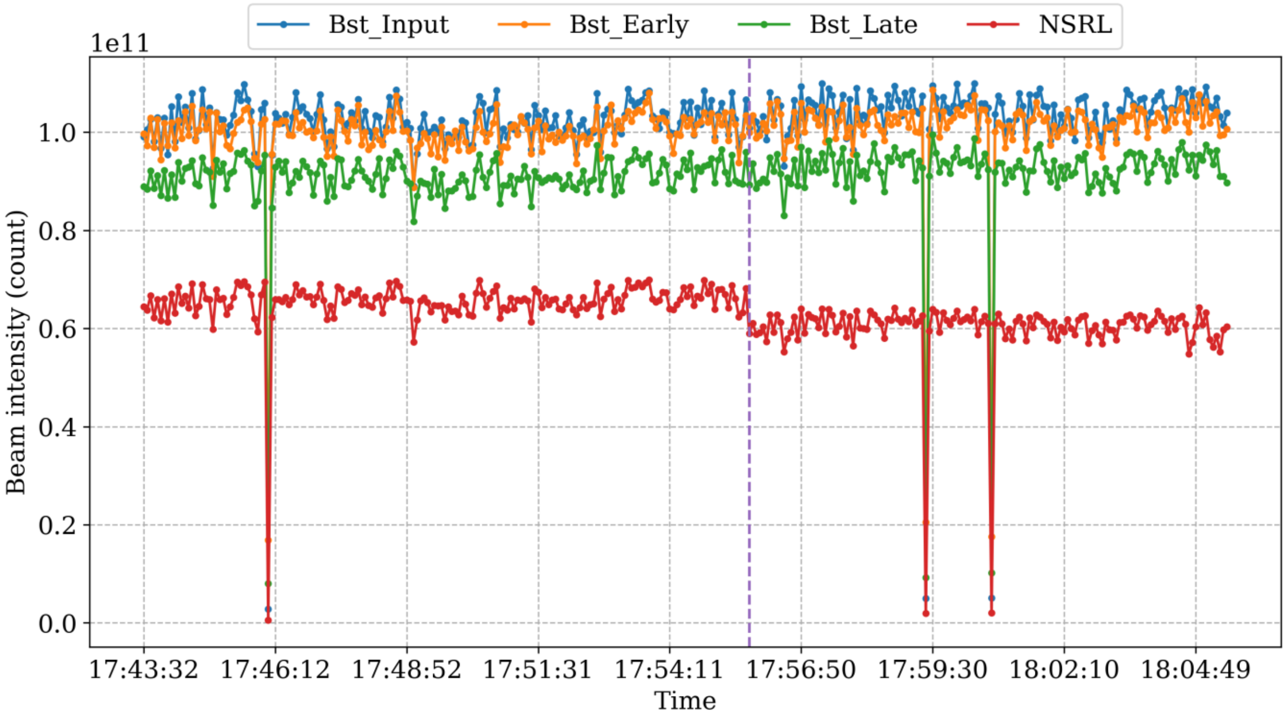
- Optimize operational bump by minimizing the residual orbit across the Booster ring

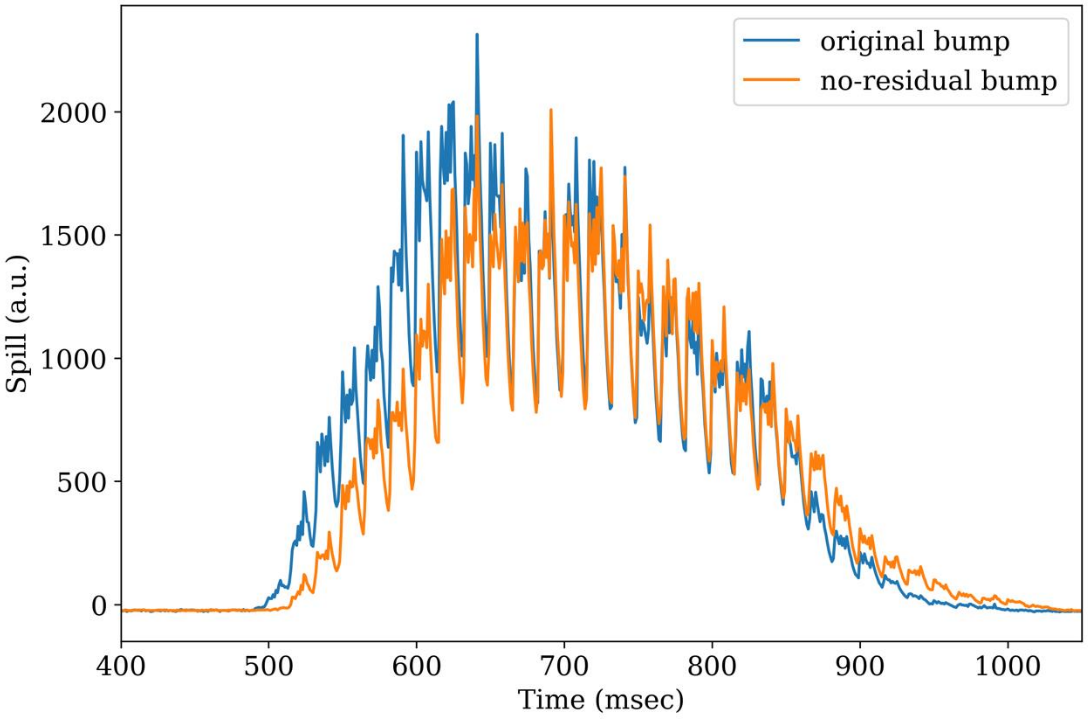


DT-assisted bump tuning

1 GeV/n Proton

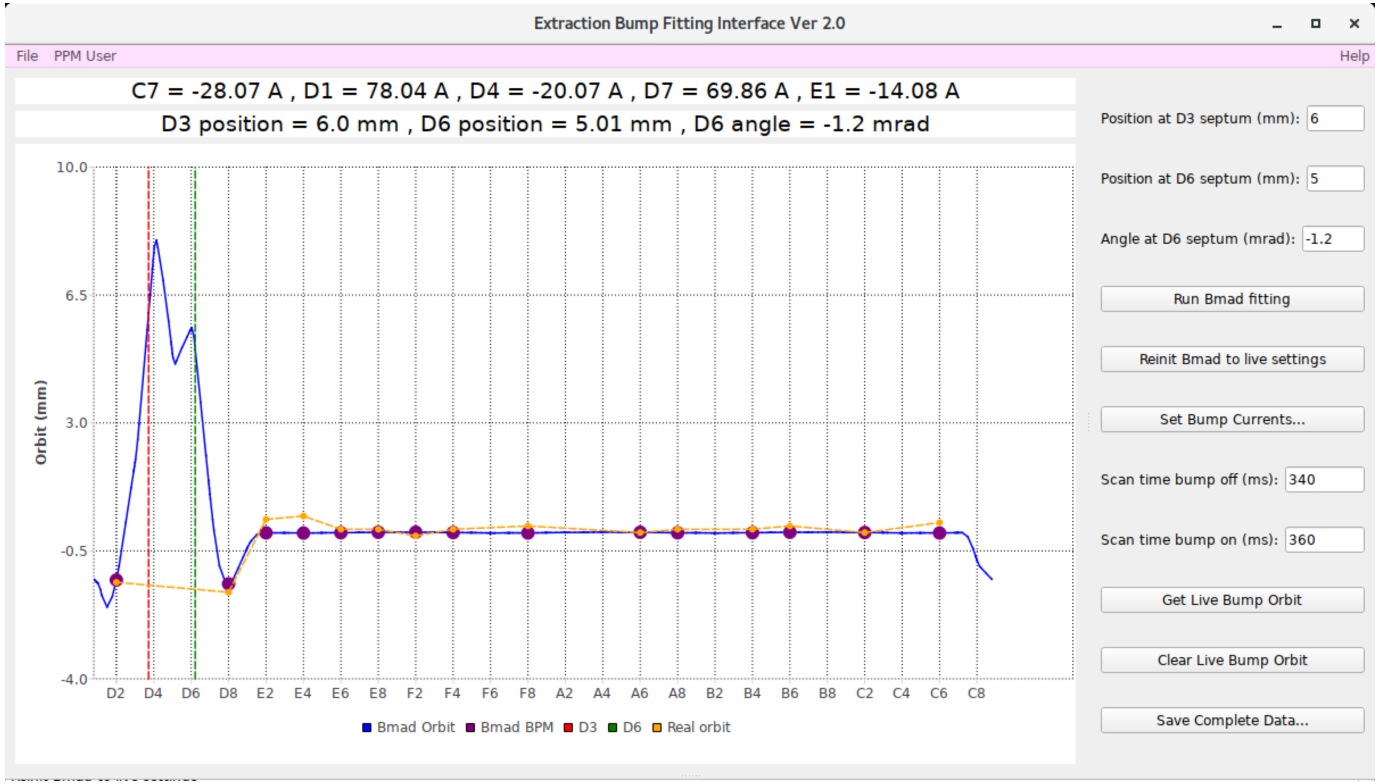
- Minimal change in intensity and spill for optimized bump with minimal residual orbit

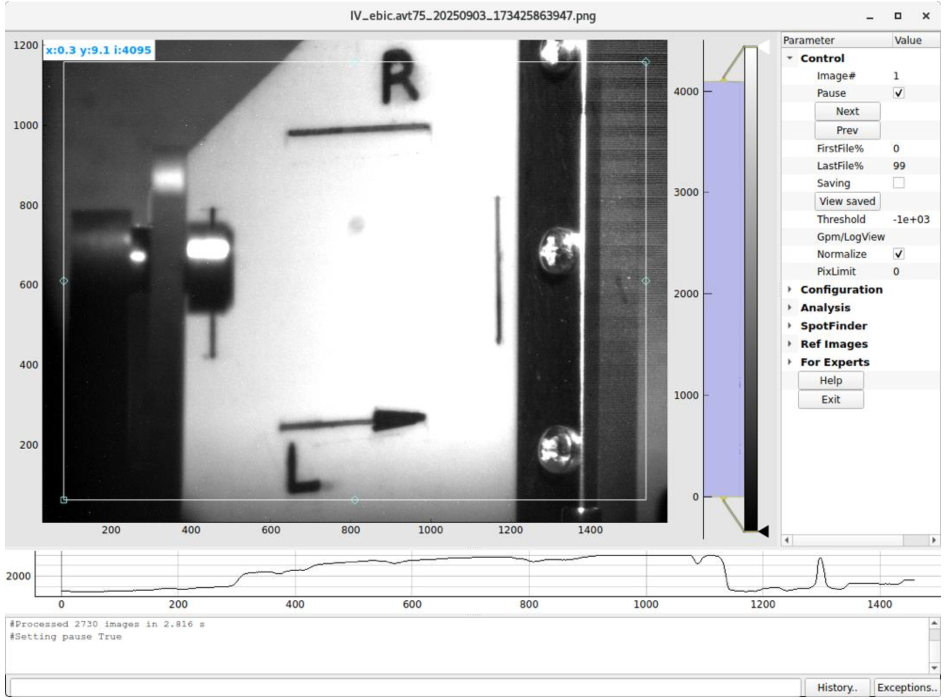




DT-assisted bump tuning

- Difficulty in recovering original design bump
  - Lack of BPMs around the two septa
  - D3 has been moved away from design location
  - D6 flag was not operational → now fixed

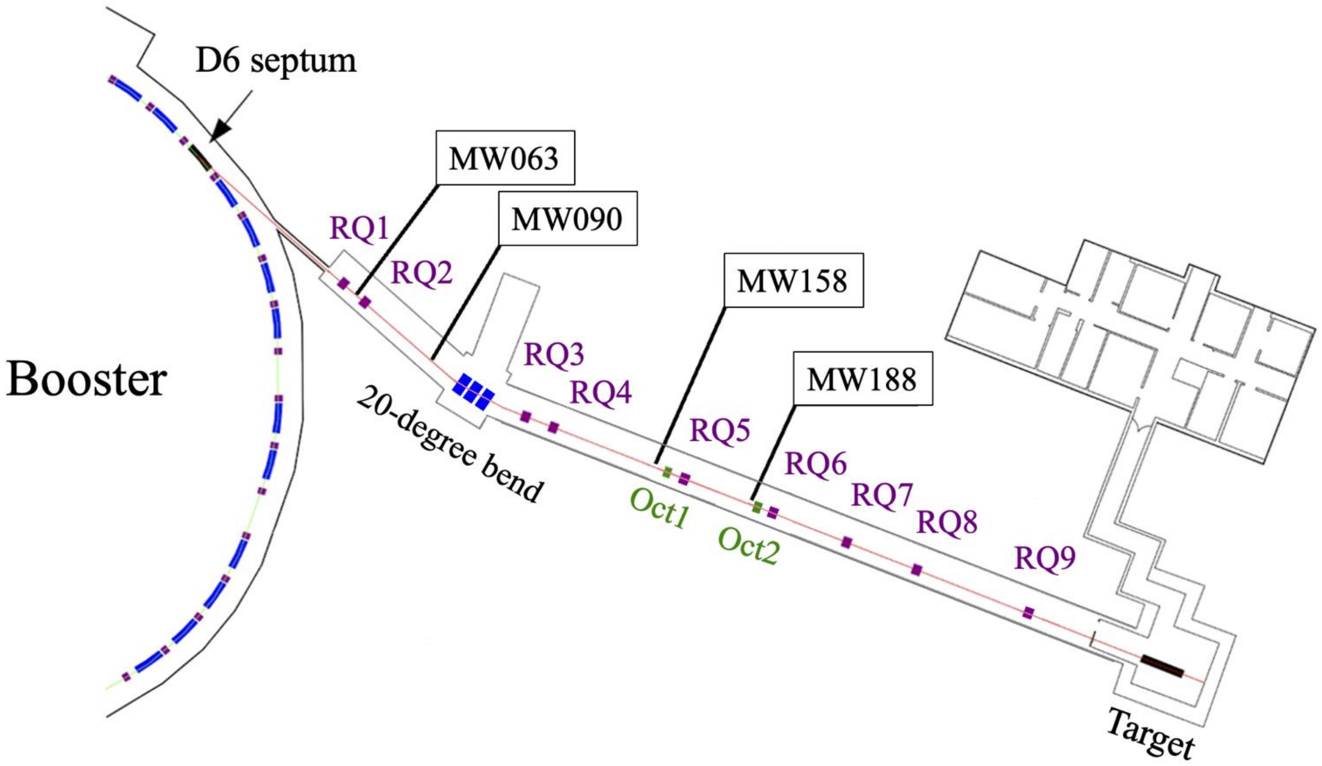




NSRL Beam Line

NSRL beam line

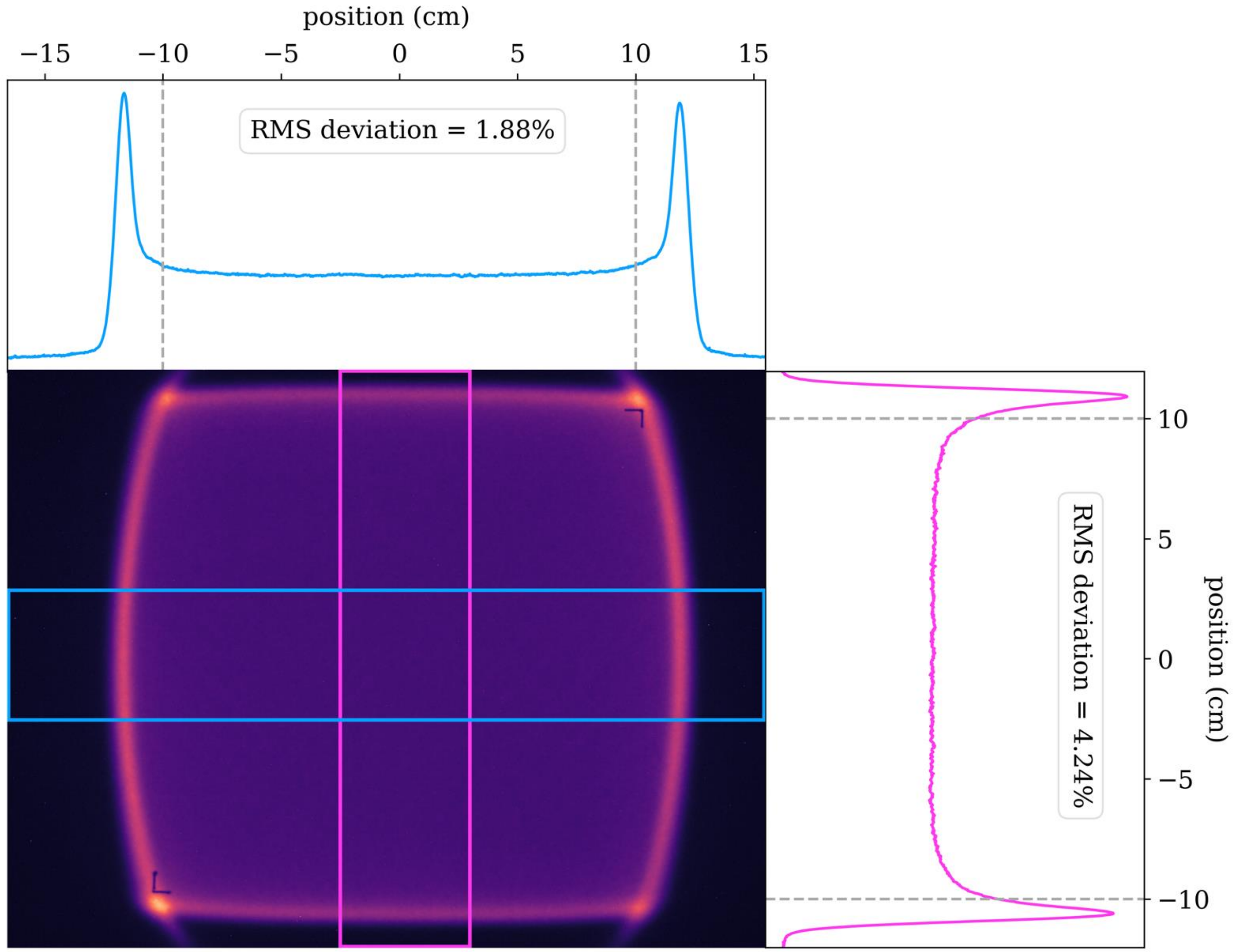
- Nine quadrupoles, three dipoles (20 degree), two octupoles, four multi-wires
- Designed to be achromatic after the 20-degree bend
- Two octupoles create uniform square beam at the target



Uniform beam with octupoles

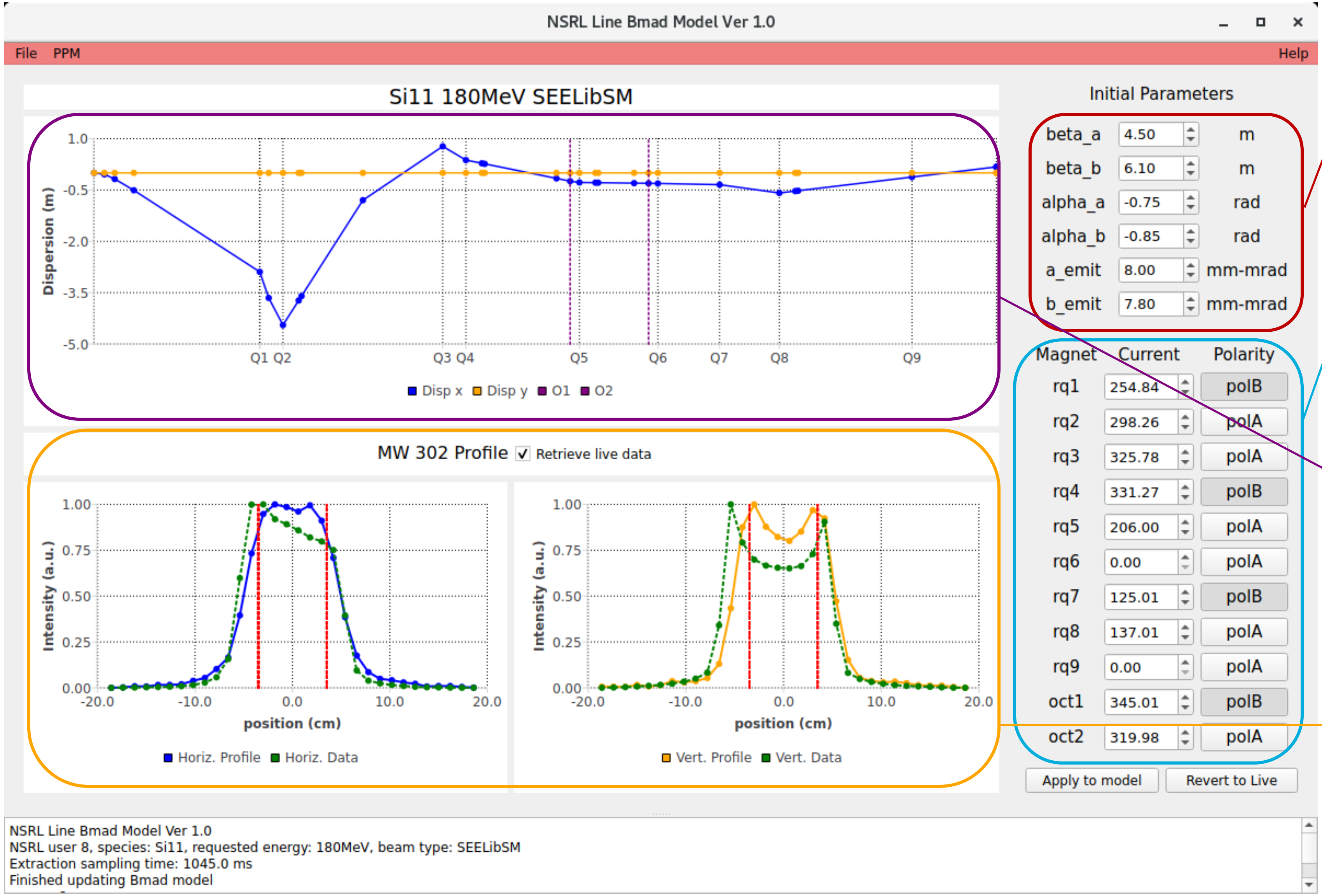
480 MeV/n Iron

- Uniformity is defined as the RMS deviation from the average beam intensity in the center uniform region
- Uniformity of $\leq 5\%$ is provided for NSRL experiments



Digital Twin for NSRL line

180 MeV/n Silicon



Initial beam parameters used by model

Currents and polarities of quadrupoles from live machine

Simulated dispersion of NSRL line using live machine info

Simulated vs. real transverse beam profile at MW302

Summary

- NSRL is a unique facility that utilizes slow extraction to provide high quality heavy-ion beam for industry and academia to conduct space radiation testing
- Booster extraction bump plays a key role in the slow extraction process, but years of empirical tuning has shifted the operational bump very far away from design
- We developed and tested a complete digital twin system for the extraction bumps, with bidirectional interaction between physical and virtual machines.
- Future bump tuning will be easier and more streamlined with the help of DT
- DT for NSRL line also under development, will facilitate beam uniformity optimization

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